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## AN INTERPOLATION PROCEDURE FOR CALCULATING ATMOSPHERIC BAND ABSORPTIONS FROM LABORATORY DATA

LEANN DROPLEMAN, LAWRENCE R. MEGILL  
AND ROBERT F. CALFEE



U. S. DEPARTMENT OF COMMERCE  
NATIONAL BUREAU OF STANDARDS

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### AN INTERPOLATION PROCEDURE FOR CALCULATING ATMOSPHERIC BAND ABSORPTIONS FROM LABORATORY DATA

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# An Interpolation Procedure for Calculating Atmospheric Band Absorptions From Laboratory Data

LeAnn Droppleman, Lawrence R. Megill, and Robert F. Calfee

A technique used for the calculation of absorption of the  $4.3\mu$  band of  $\text{CO}_2$  has been extended to the  $2.0\mu$ ,  $2.7\mu$ , and  $15\mu$  bands of  $\text{CO}_2$ . Results obtained agree favorably with the experimental data available.

## 1. Introduction

In recent years there has been an increased interest in problems associated with absorption of infrared radiation by constituents of the earth's atmosphere. Theoretical as well as experimental approaches have been made to the problem. One such attempt is that of Megill and Jammick [1961] which makes use of laboratory data to determine, by means of a regular band model, the atmospheric absorption due to the  $\text{CO}_2$  band at  $4.3\mu$ . In another part of this paper a résumé of their technique is given for the convenience of the reader.

This method has been employed for further determinations of atmospheric absorption by  $\text{CO}_2$  for the  $2\mu$ ,  $2.7\mu$ ,  $4.3\mu$  and  $15\mu$  bands. The laboratory data used for these analyses are those of Howard, Burch, and Williams [1954], hereafter referred to as HBW. The HBW report gives the results of investigations made with a low resolution instrument. The spectrometer slits were set approximately  $2000\mu$  apart.

In all the determinations made for the various  $\text{CO}_2$  bands, the effective transmission values were measured from the laboratory data at ten wave number ( $10 \text{ cm}^{-1}$ ) intervals. An average value of  $\alpha_0 = 0.064 \text{ cm}^{-1}$  was assumed for the half-width of the lines at standard atmospheric conditions  $p_0$  and  $\theta_0$ . An average line spacing

$\delta = 1.56 \text{ cm}^{-1}$  was used. Following Megill and Jamnick, corrections to the half-width were made only for pressure variations, using a constant value of temperature,  $\theta_0 \sim 290^\circ \text{ K}$ . That is  $\alpha = \alpha_0 \frac{P}{P_0}$ . From these values the absorption coefficients were calculated and used to determine the integrated band absorption  $\int A_\nu d\nu$ .

## 2. Résumé of Interpolation Method

The following is a brief review of the contents of the paper by Megill and Jamnick with some changes in notation which will be compatible with the present paper.

The basic relationship governing the absorption of energy is given by

$$I(\nu) = I_0(\nu) \exp [-k(\nu) m]. \quad (1)$$

This equation states that for radiation at any wave number  $\nu$ , the flux per unit area of radiation  $I$ , which has passed through a mass of material  $m$  is given as the product of the incident energy flux ( $I_0$ ) and the exponential of the negative product of the mass  $m$  and an absorption coefficient  $k(\nu)$  characteristic of that material. The application of this simple relationship can result in a very complex problem when one attempts to calculate  $k(\nu)$  for a given material. This is especially true for an infrared band of a complex molecule. Here a technique will be described which has been developed to allow

one to extrapolate from laboratory data to fairly general atmospheric conditions.

The calculation of  $k(v)$  involves knowledge of the position, the strength and the shape of all absorption lines near enough to the point  $v$  to affect the calculation. The summation of the effect of all these lines is used to arrive at a total value for  $k(v)$ . The integrated intensity and position are nearly independent of pressure and temperature for many applications, but the shape is a function of both.

The problem of specific concern is the absorption of infrared radiation through a non-uniform path such as the earth's atmosphere. Many molecules have a band structure consisting of nearly regularly spaced lines whose intensity varies slowly with wave number. This type of band has been studied by a number of authors - Elsasser [1938], Kaplan [1952], and Plass [1958]. Here the assumption is made that each portion of band can be represented by such a model with  $k(v)$  being calculated from

$$k(v) = \sum_i k_i(v) = \sum_i S_{oi} b(v - v_{oi}) \quad (2)$$

where  $k_i(v)$  is the contribution from the  $i$ 'th line of intensity  $S_{oi}$  with its line center at position  $v_{oi}$ . The function  $b(v - v_{oi})$  describes the line shape. It is further assumed that the pressure is such that only the Lorentz broadening need be considered so that

$$b(v - v_{oi}) = \frac{\alpha}{\pi} \frac{1}{[(v - v_{oi})^2 + \alpha^2]} , \quad (3)$$

where  $\alpha$  is the half-width of the line. The assumption of a regular band allows  $v_{oi}$  to be expressed as

$$v_{oi} = v_o + n \delta, \quad (4)$$

where  $v_o$  is taken at the center of an arbitrary line and  $\delta$  is the line spacing. Here  $n$  takes on positive and negative integral values.

Assuming all the  $S_{oi}$  are equal, they will be denoted as  $S_o$ . Under these conditions the absorption coefficient may be written

$$k(v) = \sum_{-\infty}^{\infty} \frac{S_o}{\pi} \frac{1}{[v - (v_o + n \delta)]^2 + \alpha^2} . \quad (5)$$

It has been shown by Elsasser [1938] that, given the above expression, the transmittance of the region is

$$T = \int_{-\frac{1}{2}}^{\frac{1}{2}} \exp \left[ -2 \pi y \gamma \frac{\sinh 2\pi y}{\cosh 2\pi y - \cos 2\pi x} \right] dx, \quad (6)$$

where  $x = v/\delta$ ,  $y = \alpha/\delta$ , and  $\gamma = S_o m/2 \pi \alpha$ . The temperature and pressure dependencies are included in the value used for  $\alpha$ .

These pressure and temperature dependencies of  $\alpha$  are given by

$$\alpha = \alpha_0 \left( \frac{P}{P_0} \right) \left( \frac{\theta_0}{\theta} \right)^{\frac{1}{2}}, \quad (7)$$

where  $\alpha_0$  is the line width at pressure  $P_0$  and temperature  $\theta_0$ .

Implicit in the above are the assumptions that the absorbing gas is dilute and that the population of the various states does not change with temperature; i.e.,  $S_0$  is not a function of temperature.

Utilizing the regular band model (Eq. 6), the atmospheric transmittance was calculated from data taken from low resolution experimentally determined absorption curves. An equivalent line intensity  $S_0$  at intervals of ten wave numbers was calculated for each pressure for which data were available. A plot of these values as a function of pressure was then made. If Eq. (6) were an accurate representation of the physical facts, then  $S_0(v, P)$  should be independent of pressure. It was found from these plots that  $S_0$  as here calculated is a function of pressure. Therefore, an equivalent line strength  $S_0^e(v, P)$  was defined such that

$$S_0^e(v, P) = K(v) P^a. \quad (8)$$

The absorptance in non-uniform paths was then calculated by:

1) assuming a regular band model; and 2) calculating the absorptance due to a large number of "slabs", each of which is assumed to have a

distinct temperature and pressure. The values of  $S_o^e(v, P)$  are calculated for each slab from the empirically determined table of K's and a's. In this fashion the principal effects are taken account of by theory, while a second-order correction is made using the empirically determined parameters.

After determining the emergent flux  $I(v)$ , the total band absorptance was calculated by summing the effects of each of the ten  $\text{cm}^{-1}$  intervals. This result can then be compared to experimental data. Megill and Jamnick [1961] made a comparison between calculations of absorptance in the atmosphere by this technique based on the data of HBW and data obtained on a balloon flight reported by Murcray, Brooks, Murcray, and Williams [1960].

### 3. Results

For the present study of atmospheric absorption by the several  $\text{CO}_2$  bands, the integrated absorptions were computed for each of the layers in the atmosphere. Table 1 gives a list of pressures and  $\text{CO}_2$  concentrations for which laboratory data were available. Table 2 lists the least squares fit values of K and a from which the effective line strengths  $S_o^e$  were calculated. Table 3 shows the values of total absorption  $\int A_v dv$  calculated for each of the several layers in the atmosphere. Plots of the total absorption  $\int A_v dv$  in  $\text{cm}^{-1}$  as a function of the product of pressure, P, in millimeters of mercury, and mass, m, expressed as a fraction of the atmosphere traversed are shown in

figures 1, 2, 3, and 4. In addition the results from data obtained by balloon flight are also shown on the same graphs with the appropriate predicted results.

#### 4. Conclusions

In the cases where comparisons with atmospheric data were made the agreement is good. Thus the method appears to be a feasible means of predicting atmospheric absorption by constituents which can be described by the regular band model and for which Lorentzian broadening of the lines is the principal factor in determining line shapes. Possibly, further refinements in the procedure could be attained by including temperature corrections to the line broadening. From the degree of success achieved in the case of the regular band, it seems that it may be feasible to use a similar approach to the random band model which is applicable to water vapor for example.

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TABLE 1

Combinations of pressure  $P$  and concentration of  $\text{CO}_2$   $w$  used for calculating effective line strengths  $S_0^e$  at intervals of  $10 \text{ cm}^{-1}$ .

| $\text{CO}_2$ | Band | P total<br>(mm Hg) | P partial<br>(mm Hg) | w<br>(atmo-cm) | P total<br>(mm Hg) | P partial<br>(mm Hg) | w<br>(atmo-cm) |
|---------------|------|--------------------|----------------------|----------------|--------------------|----------------------|----------------|
| $2\mu$        | 10   | 10                 | 10                   | 1730           | 100                | 50                   | 8630           |
|               | 35   | 35                 | 35                   | 378            | 200                | 10                   | 108            |
|               | 35   | 35                 | 35                   | 755            | 200                | 10                   | 432            |
|               | 35   | 35                 | 35                   | 1510           | 200                | 50                   | 540            |
|               | 35   | 35                 | 35                   | 3020           | 200                | 10                   | 1730           |
|               | 50   | 50                 | 50                   | 540            | 200                | 50                   | 2160           |
|               | 50   | 50                 | 50                   | 2160           | 200                | 50                   | 8630           |
|               | 50   | 50                 | 50                   | 8630           | 400                | 10                   | 108            |
|               | 75   | 75                 | 75                   | 809            | 400                | 10                   | 432            |
|               | 75   | 75                 | 75                   | 1620           | 400                | 10                   | 1730           |
|               | 75   | 75                 | 75                   | 3240           | 470                | 50                   | 540            |
|               | 75   | 75                 | 75                   | 6476           | 470                | 50                   | 2160           |
|               | 100  | 100                | 10                   | 432            | 470                | 50                   | 8630           |
|               | 100  | 100                | 50                   | 540            | 760                | 50                   | 540            |
|               | 100  | 100                | 10                   | 1730           | 760                | 50                   | 2160           |
|               | 100  | 100                | 50                   | 2160           | 760                | 50                   | 8630           |
| $2.7\mu$      | 1    | 1                  | 1                    | 11             | 120                | 10                   | 432            |
|               | 1    | 1                  | 1                    | 22             | 120                | 10                   | 863            |
|               | 1    | 1                  | 1                    | 43             | 120                | 10                   | 1619           |
|               | 1    | 1                  | 1                    | 86             | 126                | 0.4                  | 25             |
|               | 4    | 4                  | 4                    | 43             | 140                | 4                    | 43             |
|               | 4    | 4                  | 4                    | 86             | 140                | 4                    | 86             |
|               | 5    | 5                  | 5                    | 173            | 140                | 4                    | 173            |
|               | 5    | 5                  | 5                    | 345            | 140                | 4                    | 345            |
|               | 5    | 5                  | 5                    | 518            | 300                | 1                    | 11             |
|               | 6    | 6                  | 0.4                  | 25             | 300                | 1                    | 22             |
|               | 10   | 10                 | 10                   | 108            | 300                | 0.4                  | 25             |
|               | 10   | 10                 | 10                   | 216            | 300                | 1                    | 43             |
|               | 10   | 10                 | 10                   | 432            | 300                | 1                    | 86             |
|               | 10   | 10                 | 10                   | 863            | 306                | 4                    | 43             |
|               | 10   | 10                 | 10                   | 1619           | 306                | 4                    | 86             |
|               | 25   | 25                 | 1                    | 11             | 306                | 4                    | 173            |
|               | 25   | 25                 | 1                    | 22             | 306                | 4                    | 345            |
|               | 25   | 25                 | 0.4                  | 25             | 306                | 4                    | 648            |
|               | 25   | 25                 | 1                    | 43             | 737                | 1                    | 11             |
|               | 25   | 25                 | 1                    | 86             | 737                | 1                    | 22             |
|               | 57   | 57                 | 1                    | 11             | 737                | 1                    | 43             |
|               | 57   | 57                 | 1                    | 22             | 737                | 1                    | 86             |

Table 1 continued

| CO <sub>2</sub>       | Band | P total<br>(mm Hg) | P partial<br>(mm Hg) | w<br>(atmo-cm) | P total<br>(mm Hg) | P partial<br>(mm Hg) | w<br>(atmo-cm) |
|-----------------------|------|--------------------|----------------------|----------------|--------------------|----------------------|----------------|
| (2.7 $\mu$<br>cont'd) | 57   | 1                  | 43                   |                | 740                | 4                    | 43             |
|                       | 57   | 4                  | 43                   |                | 740                | 4                    | 86             |
|                       | 57   | 1                  | 86                   |                | 740                | 4                    | 173            |
|                       | 57   | 4                  | 86                   |                | 740                | 4                    | 345            |
|                       | 57   | 4                  | 173                  |                | 740                | 4                    | 518            |
|                       | 57   | 4                  | 345                  |                | 740                | 4                    | 648            |
|                       | 120  | 1                  | 11                   |                | 747                | 10                   | 108            |
|                       | 120  | 1                  | 22                   |                | 747                | 10                   | 863            |
|                       | 120  | 1                  | 43                   |                | 755                | 10                   | 216            |
|                       | 120  | 1                  | 86                   |                | 755                | 10                   | 432            |
| 120                   | 10   | 108                |                      |                | 755                | 10                   | 1619           |
|                       | 10   | 216                |                      |                |                    |                      |                |
| 4.3 $\mu$             | 1    | 1                  | 18                   |                | 731                | 1                    | 46             |
|                       | 1    | 1                  | 182                  |                | 731                | 1                    | 64             |
|                       | 4    | 4                  | 364                  |                | 731                | 1                    | 82             |
|                       | 5    | 1                  | 18                   |                | 734                | 1                    | 91             |
|                       | 10   | 9.8                | 104                  |                | 734                | 9.8                  | 1043           |
|                       | 10   | 4                  | 364                  |                | 735                | 1                    | 9              |
|                       | 10   | 9.8                | 1043                 |                | 735                | 1                    | 18             |
|                       | 20   | 1                  | 18                   |                | 735                | 1                    | 27             |
|                       | 20   | 1                  | 182                  |                | 735                | 1                    | 36             |
|                       | 52   | 1                  | 18                   |                | 735                | 1                    | 46             |
|                       | 100  | 9.8                | 104                  |                | 735                | 1                    | 55             |
|                       | 100  | 9.8                | 209                  |                | 735                | 1                    | 91             |
|                       | 100  | 9.8                | 1040                 |                | 735                | 9.8                  | 104            |
|                       | 100  | 9.8                | 1043                 |                | 735                | 1                    | 137            |
|                       | 103  | 1                  | 182                  |                | 735                | 1                    | 182            |
|                       | 104  | 1                  | 18                   |                | 735                | 9.8                  | 313            |
|                       | 199  | 1                  | 18                   |                | 735                | 9.8                  | 626            |
|                       | 396  | 9.8                | 104                  |                | 735                | 9.8                  | 1040           |
|                       | 396  | 9.8                | 1043                 |                | 735                | 9.8                  | 1570           |
|                       | 398  | 1                  | 18                   |                | 742                | 9.8                  | 104            |
|                       | 731  | 1                  | 18                   |                |                    |                      |                |

Table 1 continued

| CO <sub>2</sub> | Band | P total<br>(mm Hg) | P partial<br>(mm Hg) | w<br>(atmo-cm) | P total<br>(mm Hg) | P partial<br>(mm Hg) | w<br>(atmo-cm) |
|-----------------|------|--------------------|----------------------|----------------|--------------------|----------------------|----------------|
| 15 $\mu$        | 20   | 20                 | 20                   | 216            | 125                | 4                    | 173            |
|                 | 20   | 20                 | 20                   | 432            | 125                | 20                   | 216            |
|                 | 20   | 20                 | 20                   | 863            | 125                | 20                   | 432            |
|                 | 50   | 1                  | 1                    | 11             | 125                | 20                   | 863            |
|                 | 50   | 1                  | 1                    | 22             | 350                | 1                    | 11             |
|                 | 50   | 1                  | 1                    | 43             | 350                | 1                    | 22             |
|                 | 50   | 4                  | 4                    | 43             | 375                | 1                    | 43             |
|                 | 50   | 4                  | 4                    | 86             | 375                | 4                    | 43             |
|                 | 50   | 4                  | 4                    | 173            | 375                | 4                    | 86             |
|                 | 125  | 1                  | 1                    | 11             | 375                | 4                    | 173            |
|                 | 125  | 1                  | 1                    | 22             | 375                | 20                   | 216            |
|                 | 125  | 1                  | 1                    | 43             | 745                | 4                    | 43             |
|                 | 125  | 4                  | 4                    | 43             | 745                | 4                    | 86             |
|                 | 125  | 4                  | 4                    | 86             | 745                | 4                    | 173            |

TABLE 2

Least square fit values of K and a from which the effective line strengths  $S_o^e = K P^a$  were calculated. P is expressed in millimeters of mercury.

| $CO_2$<br>Band | $\nu$<br>( $cm^{-1}$ ) | K                     | a                      | $\nu$<br>( $cm^{-1}$ ) | K                     | a                      |
|----------------|------------------------|-----------------------|------------------------|------------------------|-----------------------|------------------------|
| 2u             | 4710                   | $1.93 \times 10^{-4}$ | $4.07 \times 10^{-1}$  | 5010                   | $1.34 \times 10^1$    | $-3.43 \times 10^{-1}$ |
|                | 4720                   | $1.14 \times 10^{-1}$ | $-6.19 \times 10^{-1}$ | 5020                   | $1.06 \times 10^1$    | $-3.68 \times 10^{-1}$ |
|                | 4730                   | $1.22 \times 10^{-3}$ | $2.49 \times 10^{-1}$  | 5030                   | $6.75 \times 10^0$    | $-3.36 \times 10^{-1}$ |
|                | 4740                   | $1.56 \times 10^{-2}$ | $-3.99 \times 10^{-2}$ | 5040                   | $4.66 \times 10^0$    | $-3.04 \times 10^{-1}$ |
|                | 4750                   | $4.28 \times 10^{-2}$ | $-8.86 \times 10^{-2}$ | 5050                   | $4.00 \times 10^0$    | $-2.87 \times 10^{-1}$ |
|                | 4760                   | $1.38 \times 10^{-1}$ | $-1.84 \times 10^{-1}$ | 5060                   | $3.74 \times 10^0$    | $-2.67 \times 10^{-1}$ |
|                | 4770                   | $3.17 \times 10^{-1}$ | $-2.24 \times 10^{-1}$ | 5070                   | $3.36 \times 10^0$    | $-2.18 \times 10^{-1}$ |
|                | 4780                   | $7.78 \times 10^{-1}$ | $-2.87 \times 10^{-1}$ | 5080                   | $4.01 \times 10^0$    | $-2.13 \times 10^{-1}$ |
|                | 4790                   | $1.26 \times 10^0$    | $-2.91 \times 10^{-1}$ | 5090                   | $5.87 \times 10^0$    | $-2.45 \times 10^{-1}$ |
|                | 4800                   | $2.78 \times 10^0$    | $-3.44 \times 10^{-1}$ | 5100                   | $6.83 \times 10^0$    | $-2.48 \times 10^{-1}$ |
|                | 4810                   | $5.22 \times 10^0$    | $-4.00 \times 10^{-1}$ | 5110                   | $6.13 \times 10^0$    | $-2.26 \times 10^{-1}$ |
|                | 4820                   | $3.95 \times 10^0$    | $-2.75 \times 10^{-1}$ | 5120                   | $4.97 \times 10^0$    | $-2.02 \times 10^{-1}$ |
|                | 4830                   | $6.27 \times 10^0$    | $-3.06 \times 10^{-1}$ | 5130                   | $3.24 \times 10^0$    | $-1.66 \times 10^0$    |
|                | 4840                   | $6.10 \times 10^0$    | $-2.65 \times 10^{-1}$ | 5140                   | $3.40 \times 10^0$    | $-1.86 \times 10^{-1}$ |
|                | 4850                   | $6.15 \times 10^0$    | $-2.44 \times 10^{-1}$ | 5150                   | $1.59 \times 10^0$    | $-1.65 \times 10^{-1}$ |
|                | 4860                   | $5.69 \times 10^0$    | $-2.21 \times 10^{-1}$ | 5160                   | $9.58 \times 10^{-1}$ | $-1.57 \times 10^{-1}$ |
|                | 4870                   | $5.23 \times 10^0$    | $-2.08 \times 10^{-1}$ | 5170                   | $5.46 \times 10^{-1}$ | $-1.23 \times 10^{-1}$ |
|                | 4880                   | $5.48 \times 10^0$    | $-2.25 \times 10^{-1}$ | 5180                   | $2.23 \times 10^{-1}$ | $-5.00 \times 10^{-2}$ |
|                | 4890                   | $6.10 \times 10^0$    | $-2.61 \times 10^{-1}$ | 5190                   | $1.12 \times 10^{-1}$ | $-1.85 \times 10^{-2}$ |
|                | 4900                   | $7.56 \times 10^0$    | $-2.96 \times 10^{-1}$ | 5200                   | $2.83 \times 10^{-2}$ | $1.33 \times 10^{-1}$  |
|                | 4910                   | $1.02 \times 10^1$    | $-3.35 \times 10^{-1}$ | 5210                   | $1.16 \times 10^{-2}$ | $1.96 \times 10^{-1}$  |
|                | 4920                   | $1.51 \times 10^1$    | $-3.73 \times 10^{-1}$ | 5220                   | $8.72 \times 10^{-3}$ | $1.53 \times 10^{-1}$  |
|                | 4930                   | $2.38 \times 10^1$    | $-4.13 \times 10^{-1}$ | 5230                   | $3.93 \times 10^{-3}$ | $2.11 \times 10^{-1}$  |
|                | 4940                   | $4.22 \times 10^1$    | $-4.71 \times 10^{-1}$ | 5240                   | $6.22 \times 10^{-3}$ | $1.37 \times 10^{-1}$  |
|                | 4950                   | $4.67 \times 10^1$    | $-4.51 \times 10^{-1}$ | 5250                   | $1.05 \times 10^{-3}$ | $3.42 \times 10^{-1}$  |
|                | 4960                   | $4.34 \times 10^1$    | $-4.10 \times 10^{-1}$ | 5260                   | $1.44 \times 10^{-3}$ | $3.15 \times 10^{-1}$  |
|                | 4970                   | $3.59 \times 10^1$    | $-3.61 \times 10^{-1}$ | 5270                   | $3.62 \times 10^{-4}$ | $4.71 \times 10^{-1}$  |
|                | 4980                   | $2.78 \times 10^1$    | $-3.18 \times 10^{-1}$ | 5280                   | $2.10 \times 10^{-4}$ | $4.63 \times 10^{-1}$  |
|                | 4990                   | $2.15 \times 10^1$    | $-2.93 \times 10^{-1}$ | 5290                   | $1.02 \times 10^{-5}$ | $8.92 \times 10^{-1}$  |
|                | 5000                   | $1.63 \times 10^1$    | $-2.92 \times 10^{-1}$ |                        |                       |                        |

Table 2 continued

| $\text{CO}_2$<br>Band | $\nu$<br>( $\text{cm}^{-1}$ ) | K                     | a                      | $\nu$<br>( $\text{cm}^{-1}$ ) | K                     | a                      |
|-----------------------|-------------------------------|-----------------------|------------------------|-------------------------------|-----------------------|------------------------|
| 2.7 $\mu$             | 3410                          | $2.75 \times 10^{-3}$ | $2.00 \times 10^{-1}$  | 3650                          | $8.46 \times 10^2$    | $-3.51 \times 10^{-1}$ |
|                       | 3420                          | $1.36 \times 10^{-2}$ | $7.20 \times 10^{-2}$  | 3660                          | $1.08 \times 10^3$    | $-3.80 \times 10^{-1}$ |
|                       | 3430                          | $7.28 \times 10^{-2}$ | $-8.54 \times 10^{-2}$ | 3670                          | $1.55 \times 10^3$    | $-4.14 \times 10^{-1}$ |
|                       | 3440                          | $1.25 \times 10^{-1}$ | $-7.23 \times 10^{-2}$ | 3680                          | $2.11 \times 10^3$    | $-4.39 \times 10^{-1}$ |
|                       | 3450                          | $2.35 \times 10^{-1}$ | $-4.86 \times 10^{-2}$ | 3690                          | $2.56 \times 10^3$    | $-4.56 \times 10^{-1}$ |
|                       | 3460                          | $1.67 \times 10^0$    | $-2.62 \times 10^{-1}$ | 3700                          | $2.90 \times 10^3$    | $-4.90 \times 10^{-1}$ |
|                       | 3470                          | $3.81 \times 10^0$    | $-2.96 \times 10^{-1}$ | 3710                          | $2.32 \times 10^3$    | $-4.91 \times 10^{-1}$ |
|                       | 3480                          | $1.86 \times 10^1$    | $-4.64 \times 10^{-1}$ | 3720                          | $1.51 \times 10^3$    | $-4.32 \times 10^{-1}$ |
|                       | 3490                          | $3.76 \times 10^1$    | $-4.89 \times 10^{-1}$ | 3730                          | $4.67 \times 10^2$    | $-3.84 \times 10^{-1}$ |
|                       | 3500                          | $7.82 \times 10^1$    | $-5.26 \times 10^{-1}$ | 3740                          | $1.56 \times 10^2$    | $-2.90 \times 10^{-1}$ |
|                       | 3510                          | $1.52 \times 10^2$    | $-5.45 \times 10^{-1}$ | 3750                          | $4.03 \times 10^1$    | $-1.80 \times 10^{-1}$ |
|                       | 3520                          | $2.78 \times 10^2$    | $-5.41 \times 10^{-1}$ | 3760                          | $1.19 \times 10^1$    | $-1.19 \times 10^{-1}$ |
|                       | 3530                          | $4.17 \times 10^2$    | $-5.12 \times 10^{-1}$ | 3770                          | $1.21 \times 10^0$    | $1.28 \times 10^{-1}$  |
|                       | 3540                          | $6.31 \times 10^2$    | $-4.96 \times 10^{-1}$ | 3780                          | $3.60 \times 10^{-1}$ | $2.03 \times 10^{-1}$  |
|                       | 3550                          | $8.24 \times 10^2$    | $-4.60 \times 10^{-1}$ | 3790                          | $4.18 \times 10^{-2}$ | $4.52 \times 10^{-1}$  |
|                       | 3560                          | $1.01 \times 10^3$    | $-4.29 \times 10^{-1}$ | 3800                          | $3.36 \times 10^{-2}$ | $4.08 \times 10^{-1}$  |
|                       | 3570                          | $1.34 \times 10^3$    | $-4.17 \times 10^{-1}$ | 3810                          | $9.56 \times 10^{-3}$ | $4.73 \times 10^{-1}$  |
|                       | 3580                          | $1.63 \times 10^3$    | $-4.01 \times 10^{-1}$ | 3820                          | $1.96 \times 10^{-3}$ | $6.72 \times 10^{-1}$  |
|                       | 3590                          | $1.66 \times 10^3$    | $-3.78 \times 10^{-1}$ | 3830                          | $8.19 \times 10^{-3}$ | $3.66 \times 10^{-1}$  |
|                       | 3600                          | $1.30 \times 10^3$    | $-3.05 \times 10^{-1}$ | 3840                          | $2.07 \times 10^{-3}$ | $4.98 \times 10^{-1}$  |
|                       | 3610                          | $1.35 \times 10^3$    | $-3.28 \times 10^{-1}$ | 3850                          | $1.62 \times 10^{-4}$ | $8.59 \times 10^{-1}$  |
|                       | 3620                          | $1.05 \times 10^3$    | $-3.16 \times 10^{-1}$ | 3860                          | $1.74 \times 10^{-1}$ | $-3.08 \times 10^{-1}$ |
|                       | 3630                          | $8.66 \times 10^2$    | $-3.25 \times 10^{-1}$ | 3870                          | $2.58 \times 10^{-2}$ | $-7.01 \times 10^{-2}$ |
|                       | 3640                          | $7.95 \times 10^2$    | $-3.36 \times 10^{-1}$ | 3880                          | $4.53 \times 10^{-3}$ | $5.30 \times 10^{-2}$  |
| 4.3 $\mu$             | 2200                          | $5.55 \times 10^0$    | $-2.26 \times 10^{-1}$ | 2330                          | $5.06 \times 10^4$    | $-5.50 \times 10^{-1}$ |
|                       | 2210                          | $1.26 \times 10^2$    | $-6.65 \times 10^{-1}$ | 2340                          | $7.40 \times 10^4$    | 0.0                    |
|                       | 2220                          | $1.07 \times 10^2$    | $-4.48 \times 10^{-1}$ | 2350                          | $8.37 \times 10^4$    | 0.0                    |
|                       | 2230                          | $5.67 \times 10^2$    | $-5.59 \times 10^{-1}$ | 2360                          | $8.42 \times 10^4$    | $-3.39 \times 10^{-1}$ |
|                       | 2240                          | $1.15 \times 10^3$    | $-5.53 \times 10^{-1}$ | 2370                          | $6.75 \times 10^4$    | $-7.79 \times 10^{-1}$ |
|                       | 2250                          | $1.01 \times 10^3$    | $-3.34 \times 10^{-1}$ | 2380                          | $1.79 \times 10^4$    | $-7.71 \times 10^{-1}$ |
|                       | 2260                          | $4.58 \times 10^3$    | $-4.50 \times 10^{-1}$ | 2390                          | $1.73 \times 10^4$    | $-8.89 \times 10^{-1}$ |
|                       | 2270                          | $7.97 \times 10^3$    | $-4.45 \times 10^{-1}$ | 2400                          | $4.28 \times 10^3$    | $-8.87 \times 10^{-1}$ |
|                       | 2280                          | $1.51 \times 10^4$    | $-4.48 \times 10^{-1}$ | 2410                          | $1.25 \times 10^2$    | $-4.43 \times 10^{-1}$ |
|                       | 2290                          | $2.57 \times 10^4$    | $-5.60 \times 10^{-1}$ | 2420                          | $5.96 \times 10^1$    | $-4.48 \times 10^{-1}$ |
|                       | 2300                          | $1.49 \times 10^4$    | $-3.32 \times 10^{-1}$ | 2430                          | $2.95 \times 10^0$    | $-12.0 \times 10^{-1}$ |
|                       | 2310                          | $3.68 \times 10^4$    | $-3.31 \times 10^{-1}$ | 2440                          | $1.31 \times 10^0$    | $-5.56 \times 10^{-2}$ |
|                       | 2320                          | $6.40 \times 10^4$    | $-3.39 \times 10^{-1}$ |                               |                       |                        |

Table 2 continued

| CO <sub>2</sub><br>Band | $\nu$<br>(cm <sup>-1</sup> ) | K                    | a                      | $\nu$<br>(cm <sup>-1</sup> ) | K                     | a                      |
|-------------------------|------------------------------|----------------------|------------------------|------------------------------|-----------------------|------------------------|
| 15 $\mu$                | 580                          | 1.69x10 <sup>2</sup> | -6.34x10 <sup>-1</sup> | 710                          | 2.67x10 <sup>3</sup>  | -3.65x10 <sup>0</sup>  |
|                         | 590                          | 9.38x10 <sup>1</sup> | -3.00x10 <sup>-1</sup> | 720                          | 1.15x10 <sup>3</sup>  | -3.35x10 <sup>0</sup>  |
|                         | 600                          | 4.27x10 <sup>1</sup> | -3.88x10 <sup>-1</sup> | 730                          | 5.32x10 <sup>2</sup>  | -3.08x10 <sup>0</sup>  |
|                         | 610                          | 8.89x10 <sup>1</sup> | -6.50x10 <sup>-1</sup> | 740                          | 2.85x10 <sup>2</sup>  | -2.67x10 <sup>0</sup>  |
|                         | 620                          | 3.44x10 <sup>2</sup> | -2.06x10 <sup>0</sup>  | 750                          | 1.53x10 <sup>2</sup>  | -2.09x10 <sup>0</sup>  |
|                         | 630                          | 4.25x10 <sup>3</sup> | -6.04x10 <sup>0</sup>  | 760                          | 1.36x10 <sup>2</sup>  | -2.87x10 <sup>0</sup>  |
|                         | 640                          | 2.34x10 <sup>3</sup> | -2.34x10 <sup>0</sup>  | 770                          | 4.89x10 <sup>1</sup>  | -3.27x10 <sup>0</sup>  |
|                         | 650                          | 8.31x10 <sup>3</sup> | -3.34x10 <sup>0</sup>  | 780                          | 2.46x10 <sup>1</sup>  | -3.66x10 <sup>0</sup>  |
|                         | 660                          | 1.84x10 <sup>4</sup> | -4.13x10 <sup>0</sup>  | 790                          | 8.16x10 <sup>0</sup>  | -2.77x10 <sup>0</sup>  |
|                         | 670                          | 3.65x10 <sup>4</sup> | -5.29x10 <sup>0</sup>  | 800                          | 5.96x10 <sup>0</sup>  | -2.83x10 <sup>0</sup>  |
|                         | 680                          | 1.49x10 <sup>4</sup> | -3.52x10 <sup>0</sup>  | 810                          | 2.15x10 <sup>0</sup>  | -1.67x10 <sup>0</sup>  |
|                         | 690                          | 9.49x10 <sup>3</sup> | -3.13x10 <sup>0</sup>  | 820                          | 5.65x10 <sup>-1</sup> | -9.84x10 <sup>-2</sup> |
|                         | 700                          | 4.50x10 <sup>3</sup> | -2.93x10 <sup>0</sup>  | 830                          | 6.96x10 <sup>-2</sup> | 2.14x10 <sup>0</sup>   |

TABLE 3  
 Values of  $\int A_\nu d\nu$  determined for the various layers in the atmosphere as a function of the product of pressure,  $P$ , in millimeters of mercury and the mass,  $m$ , expressed as a fraction of the atmosphere traversed.

| P m<br>(mm Hg) | 2 $\mu$ Band | 2.7 $\mu$ Band | 4.3 $\mu$ Band | 15 $\mu$ Band |
|----------------|--------------|----------------|----------------|---------------|
| 0.019          | 1.11         | 5.92           | 19.7           | 7.5           |
| 0.076          | 1.74         | 9.96           | 33.6           | 12.8          |
| 0.171          | 2.32         | 13.6           | 45.3           | 17.7          |
| 0.304          | 2.86         | 17.1           | 55.4           | 21.2          |
| 0.475          | 3.39         | 20.3           | 64.0           | 26.4          |
| 0.684          | 3.90         | 23.5           | 71.2           | 30.4          |
| 0.931          | 4.40         | 26.5           | 77.4           | 34.2          |
| 1.22           | 5.36         | 32.4           | 87.5           | 41.4          |
| 1.90           | 5.82         | 35.2           | 91.7           | 44.8          |
| 2.30           | 6.28         | 37.9           | 95.4           | 48.0          |
| 2.74           | 6.74         | 40.6           | 98.8           | 51.1          |
| 3.21           | 7.19         | 43.2           | 102.           | 54.1          |
| 3.72           | 7.63         | 45.8           | 105.           | 56.9          |
| 4.28           | 8.07         | 48.3           | 108.           | 59.7          |
| 4.86           | 8.50         | 50.8           | 110.           | 62.3          |
| 5.49           | 8.93         | 53.3           | 112.           | 64.9          |
| 6.16           | 9.35         | 55.7           | 115.           | 67.4          |
| 6.86           | 9.77         | 58.1           | 117.           | 69.7          |
| 7.60           | 10.2         | 60.4           | 119.           | 72.0          |
| 17.1           | 14.3         | 82.5           | 134.           | 91.2          |
| 30.4           | 18.1         | 102.           | 143.           | 105.          |
| 47.5           | 21.7         | 118.           | 150.           | 115.          |
| 68.4           | 25.3         | 134.           | 156.           | 123.          |
| 93.1           | 28.7         | 147.           | 160.           | 130.          |
| 122.           | 32.1         | 159.           | 164.           | 136.          |
| 154.           | 35.4         | 170.           | 167.           | 142.          |
| 190.           | 38.6         | 180.           | 170.           | 147.          |
| 230.           | 41.7         | 188.           | 172.           | 151.          |
| 274.           | 44.8         | 196.           | 176.           | 155.          |
| 321.           | 47.9         | 203.           | 177.           | 159.          |
| 372.           | 51.0         | 209.           | 179.           | 162.          |
| 428.           | 53.9         | 215.           | 181.           | 166.          |
| 486.           | 56.9         | 220.           | 182.           | 169.          |
| 549.           | 59.8         | 224.           | 184.           | 171.          |
| 616.           | 62.6         | 228.           | 185.           | 174.          |
| 686.           | 65.5         | 232.           | 187.           | 176.          |
| 760.           | 68.2         | 236.           | 188.           | 178.          |

ATMOSPHERIC ABSORPTION BY  $2\mu$   $\text{CO}_2$

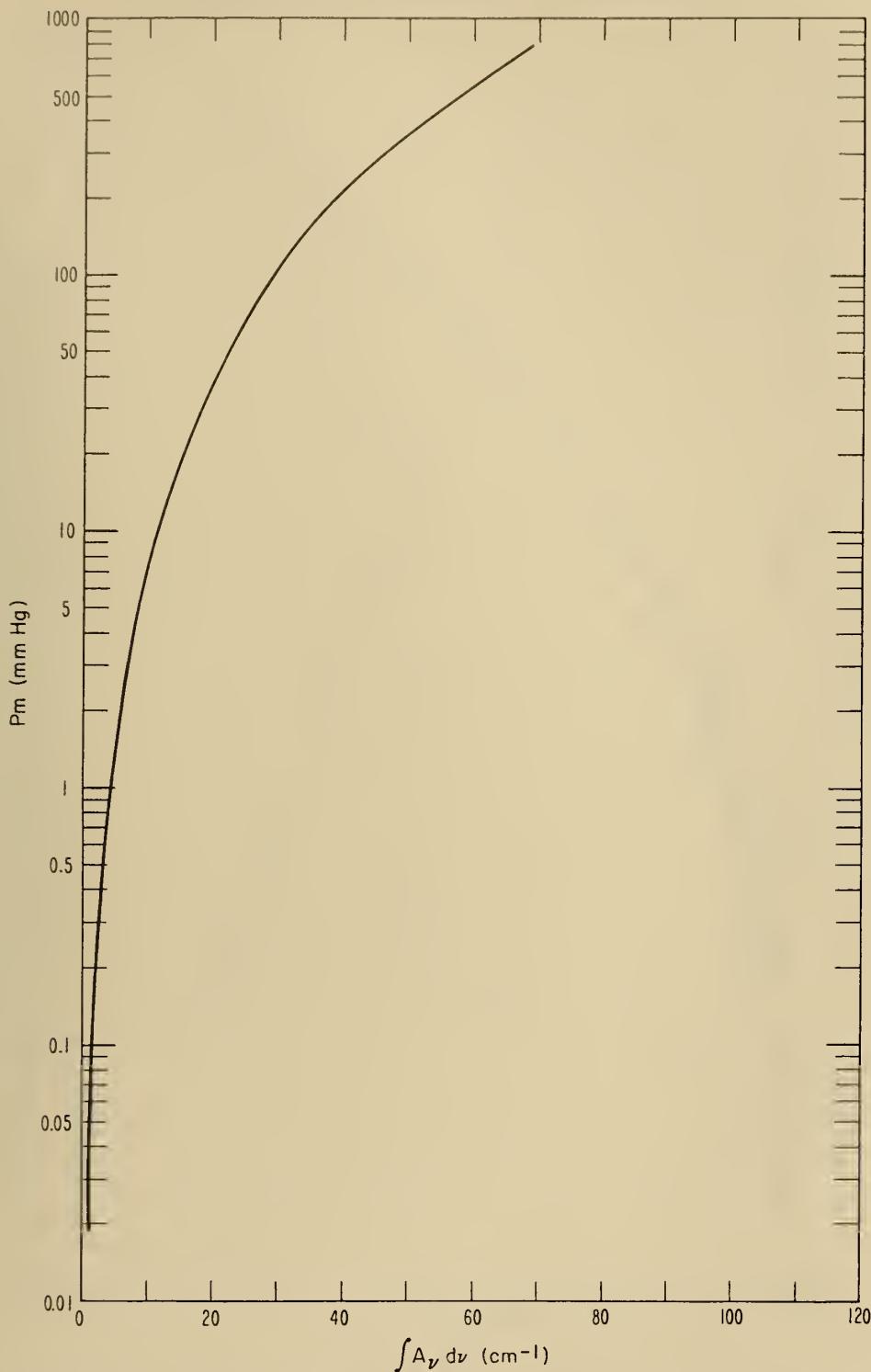


Figure 1. The total absorption of the  $2.0\mu$  band of  $\text{CO}_2$  as a function of the pressure in an isothermal atmosphere.

ATMOSPHERIC ABSORPTION BY  $2.7\mu$  CO<sub>2</sub>

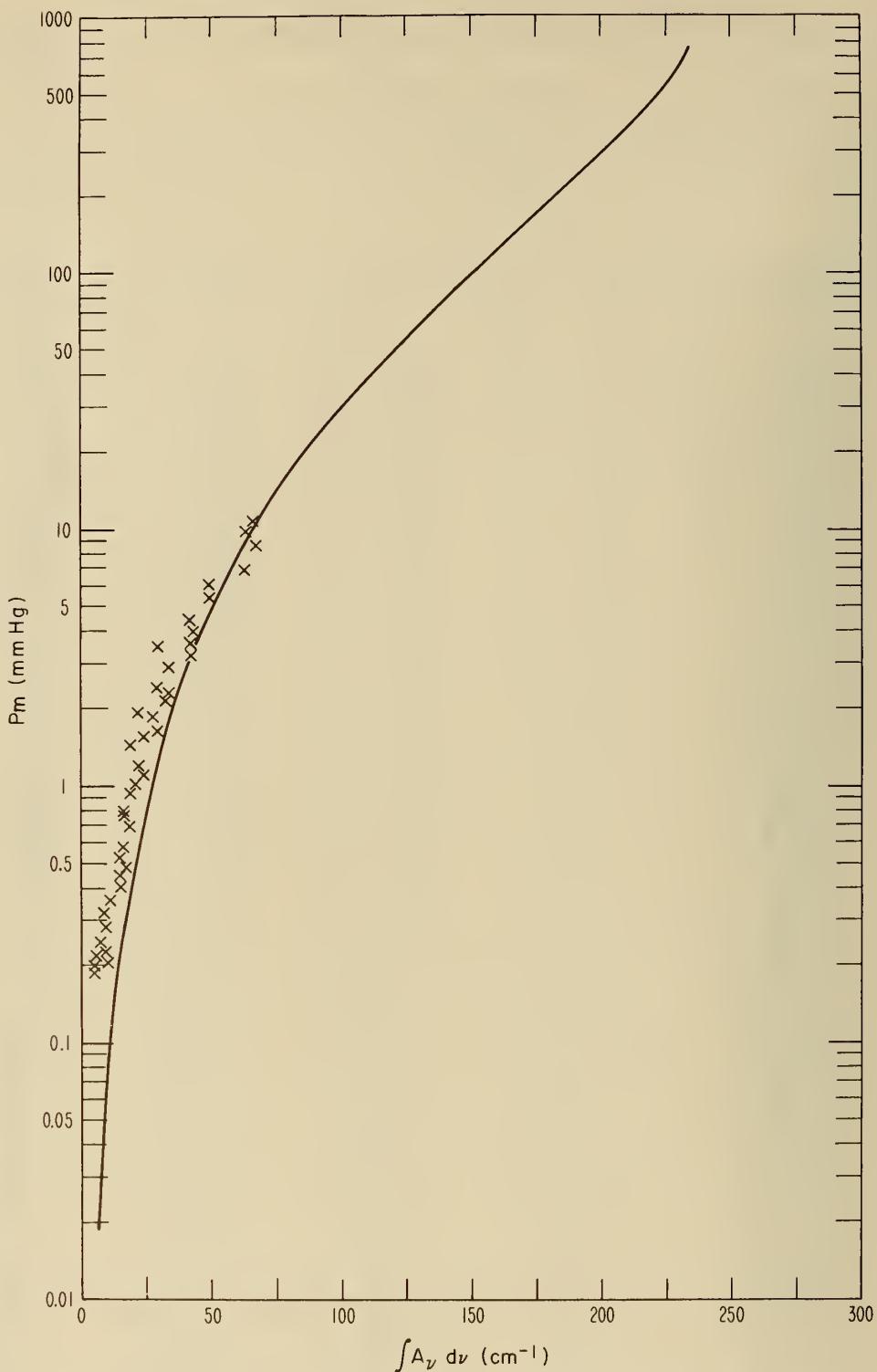


Figure 2. Atmospheric absorption of the  $2.7\mu$  band of CO<sub>2</sub> is shown as a function of pressure. The data obtained from the balloon flight of Murcray et. al. are represented by x. An isothermal atmosphere is assumed.

ATMOSPHERIC ABSORPTION BY  $4.3\mu$  CO<sub>2</sub>

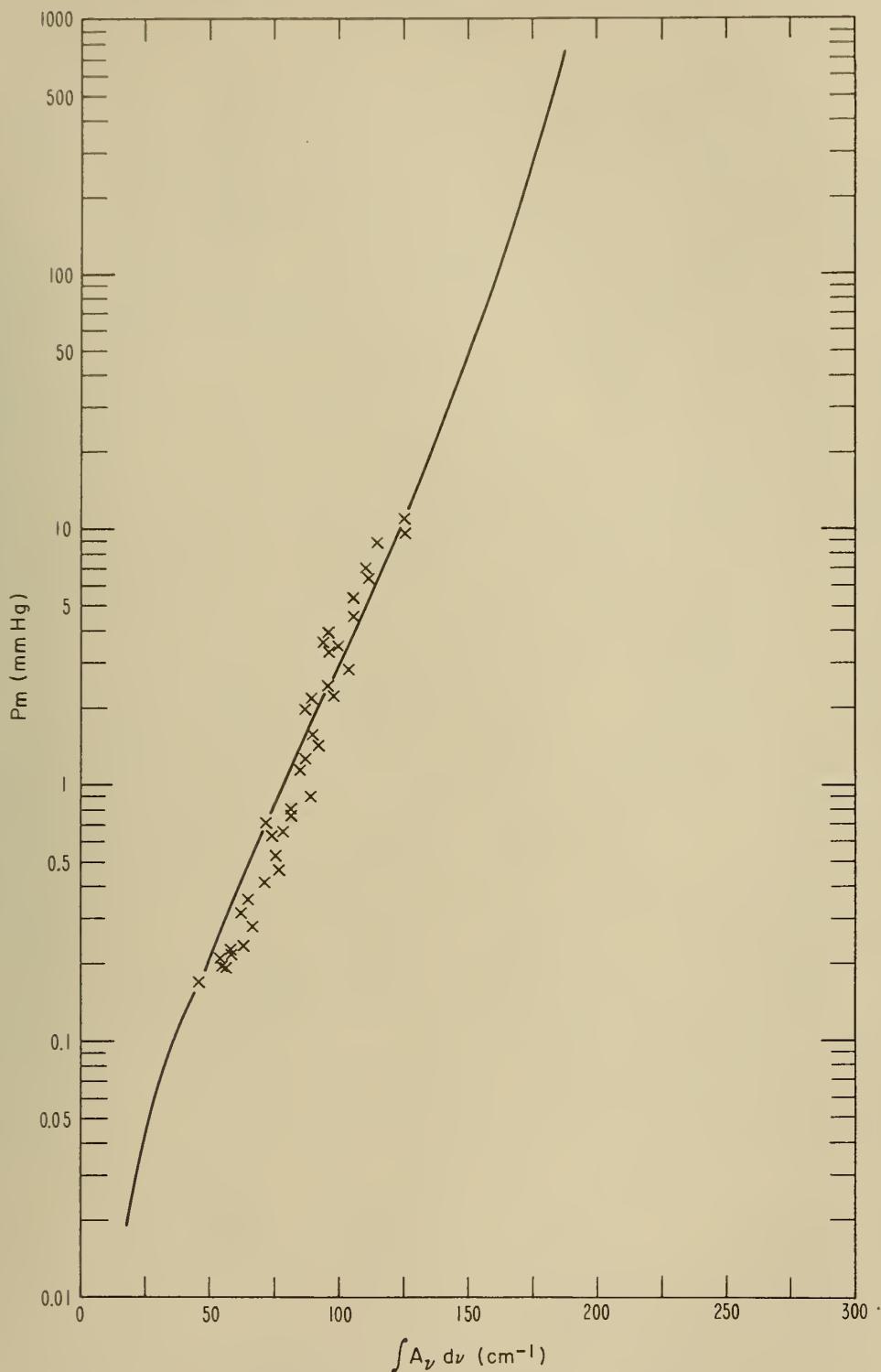


Figure 3. Atmospheric absorption of the  $4.3\mu$  band of CO<sub>2</sub> is shown as a function of pressure. The data obtained from the balloon flight of Murcray et. al. are represented by x. An isothermal atmosphere is assumed.

ATMOSPHERIC ABSORPTION BY  $15\mu$   $\text{CO}_2$

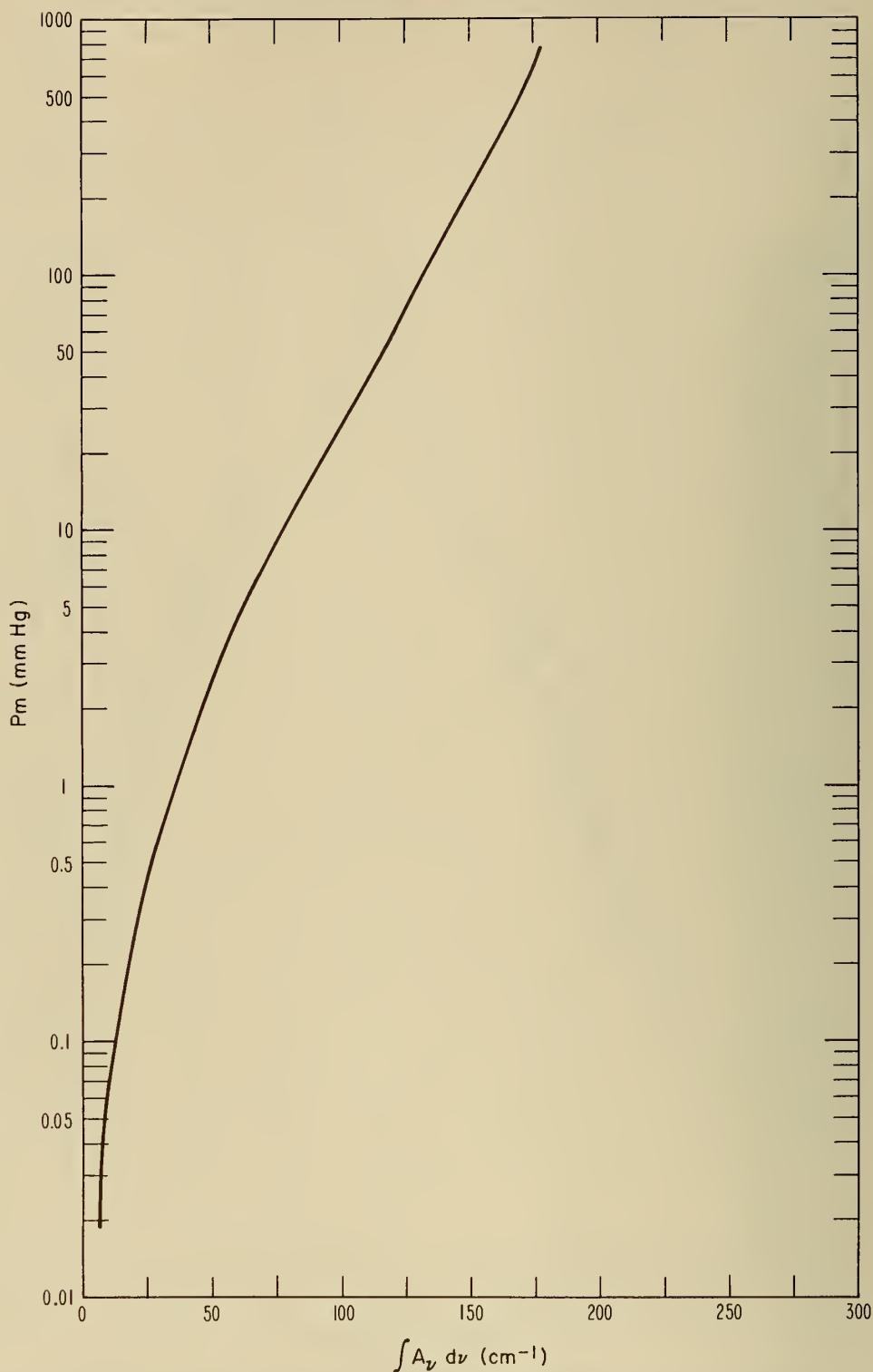


Figure 4. The total absorption of the  $15\mu$  band of  $\text{CO}_2$  as a function of the pressure in an isothermal atmosphere.

S. DEPARTMENT OF COMMERCE

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